

# Temporal analysis for multi-hazard risk assessment of rice cultivation in coastal areas: a case study of Soc Trang, Vietnam

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**Abstract.** Rice is an important human crop and rice cultivation is threatened due to natural disasters, leading to negative effects on national and global food security. Natural disasters, such as tropical cyclones and saline intrusion, have dramatic influences in coastal regions. To investigate possible impacts of these disasters on rice cultivation, it needs an efficient tool to assess potential disaster impacts and a risk index is highly applicable. Therefore, this study aims at establishing a risk assessment of rice production in coastal areas under the effects of tropical cyclones and saline intrusion. We adopted the risk definition introduced by [1] in which risk is a function of hazard, exposure and, vulnerability. Multiple hazards of tropical cyclones and saline intrusion were indicated by their frequency and severity at some critical levels of 25%, 50% and, >50% rice yield reduction. Each hazard was weighted by its damage to rice yield. The exposure and vulnerability of rice crops are evaluated at different growing phases. The tropical cyclone hazard index was ranked *high* and *very high* in the wet season while the salinity hazard index was ranked *very high* in the dry season. Due to the combined effects of tropical cyclones and salinity, rice crop is highly susceptible during the reproduction phase and at the panicle initiation stage particularly. Based on the cropping calendar of My Xuyen, the period of October-November was the *very high* vulnerability period since it had the largest rice cultivable area and rice crops were at the reproduction phase. This result shows that rice crops are at *high* risk in October and November. Noticeably, saline intrusion reaches the highest level in April and May, but no risk is at this period because of no rice crop cultivated. This can reflect a measure to reduce risk by adjusting the cropping calendar.

## 1 Introduction

According to [2] natural disasters caused damages to agricultural productions, including crops and livestock, about USD 93 billion in developing countries in a decade (2005-2014). Among these natural disasters, tropical cyclones are one of the main disastrous phenomena causing considerable damages around the world which cause damage of USD 26 billion

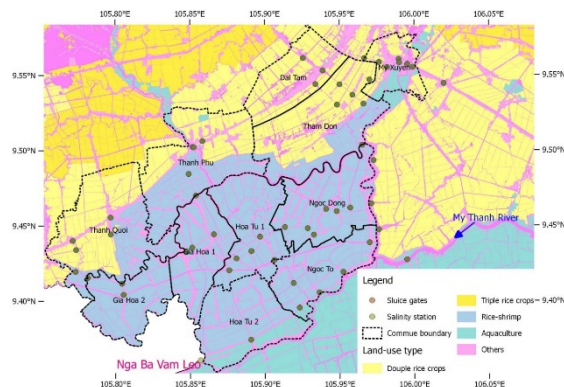
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annually [3]. In addition, there is an annual loss of approximately USD 12 billion due to saline-affected land [4]. The mentioned damaged phenomena are the major factors affecting coastal areas.

The Vietnamese Mekong Delta (VMD) is located downstream of the Mekong River which is one of the largest rivers in the world [5]. The VMD is a crucial economic region in Vietnam. Moreover, it plays an important role in ensuring food security not only for Vietnam but also for the world since the VMD contributes up to 90% to the annual rice export of Vietnam [6]. With the land resources of approximately 4 million ha, three-quarters of this area is used for agricultural production [7]. Therefore, rice production in the coastal VMD is facing challenges of tropical cyclones and saline intrusion. For example, Soc Trang is a coastal province, dealing with these challenges. Although Soc Trang is a coastal province, rice is the major agricultural product. Consequently, rice cultivation in Soc Trang is at risk of tropical cyclones and saline intrusion effects. Generally, to reduce the risk of these events, it needs to conduct a risk assessment to evaluate how rice crops can be damaged. Risk has resulted from the interaction of hazard and vulnerability [8]. In order to assess risk, it requires hazard and vulnerability assessment. The outputs of these assessments support the decision-making process.

There are some methods to assess hazard and vulnerability using indicators, field or lab experiments, and numerical models [9–21]. In comparison, using indicators is a rapid and simple method compared to the others mentioned. For instance, [22] developed a coastal city flood vulnerability index which is able to assess vulnerability to flood and evaluate adaptation options. [13] applied this index to evaluate the impacts of the projected climate change and sea-level rise on flood vulnerability in the VMD. It is determined that the vulnerability index is an effective and rapid tool to assist managers and decision-makers in assessing the impacts of predicted scenarios and improving decision-making procedures. The outputs resulted in applying this index enhance mitigation and adaptation strategies. Therefore, this study is conducted to establish a risk assessment of rice production due to the effects of tropical cyclones and saline intrusion. We assessed the impacts of tropical cyclones and saline intrusion on rice production in a coastal area (My Xuyen district, Soc Trang province, Vietnam, presented in Fig. 1) by using the risk definition of [1]. Based on this definition, risk includes hazard, exposure, and vulnerability components. Rice is an important food crop and is grown seasonally, so rice crops are not always available on the field. This suggests that a temporal analysis should be taken into account for the risk assessment. The outputs of the risk assessment help to mitigate and reduce the impacts of tropical cyclones and saline intrusion on rice cultivation.



**Fig. 1.** Land-use map in 2010 of My Xuyen district.

## 2 Methods

### 2.1 Risk definition

To identify the natural hazard risk, we used the definition of [1] in which risk is defined as a function of hazards and consequences which present the impacts of the hazardous events. In a hazardous event, its impacts are highly dependent on vulnerability and exposure. Therefore, the risk is defined by the three components of hazard, exposure, and vulnerability (Equation 1).

$$\text{risk} = f(\text{hazard, exposure, vulnerability}) \quad (1)$$

Hazard describes the probability of occurrence and intensity of natural or human-induced events such as storms, floods, and saline intrusion. Exposure shows the presence of people, infrastructure, livelihoods, environmental functions, services, etc. in the region that could be affected by the events. Vulnerability is identified as the extent of harm, including sensitivity/susceptibility and resilience. There is a broad set of elements of a system that is suffering from natural disasters. This set can be characterized by hydrogeological, social, and economic components [13,23].

### 2.2 Multiple natural hazard assessment

In order to assess natural hazards, the main hazardous events which cause considerable damages to agricultural production are selected for the assessment. Identifying and assessing hazardous events help to understand their nature and behavior, suggesting awareness and planning for disaster mitigation strategies. The natural hazards were assessed in terms of frequency, affected areas, and degree of severity. In reality, a number of natural events threaten agricultural production in the coastal area, such as saline intrusion, tropical cyclones, tornadoes, etc. These threats were selected for multi-hazards assessment based on their damages on agricultural crops in the study area and this was observed by the Department of Agriculture and Rural Development of My Xuyen district. We assessed the impacts of multi-hazards on agricultural crops, focusing on rice crops. The agricultural crops are only influenced by the natural hazards during their cultivated durations which are represented by their cropping calendars. The major land-use types in My Xuyen district are agriculture and aquaculture, consisting of intensive rice farming, intensive shrimp farming, and rice-shrimp farming [24]. Therefore, a temporal analysis is important for the hazard assessment and its temporal resolution should be fine enough to present seasonal variations of the cropping systems. In this study, the monthly interval is reasonable for presenting the cropping calendar of each farming system.

According to the recent reports on natural disaster prevention and control of My Xuyen district, saline intrusion and tropical cyclones are the most dangerous phenomena. These phenomena have caused substantial damages to agricultural cultivation recently. Therefore, these two events are considered for multiple hazards assessment. Hazard indexes are calculated by the below equation (Equation 2).

$$HI = \sum_{i=1}^n w_i HI_i \quad (2)$$

where  $HI$  is multiple hazard index;  $HI_i$  is the hazard index of phenomenon  $i$ ;  $w_i$  is the weight of phenomenon  $i$ .  $HI_i$  of each phenomenon is computed based on its frequency and intensity. The hazard index of each phenomenon should be normalized due to different ranges of the hazard index. We used the weights in the calculation of the hazard index because this helps to prioritize the importance of each phenomenon. The weight of a phenomenon is simply identified as the damage percentage caused by that phenomenon of the total damage.

### 2.2.1 Tropical cyclones

Tropical cyclones are one of the most destructive natural hazards not only in Vietnam but also over the world. They affect large areas depending on the intensity and track of the tropical cyclones. [25] defined the warning area due to the tropical cyclones within an 800 km radius. Therefore, we analyzed the tropical cyclones that occurred within a circle whose radius is 800 km from My Xuyen district. The tropical cyclones mentioned in this study are tropical storms or greater events (e.g. severe tropical storms, typhoons, or hurricanes). Data of tropical cyclones, which were recorded from 1951 to 2019 by the Japan Meteorological Agency, were used for the hazard assessment. The data contain characteristic features of tropical cyclone tracks for every six hours. First, the eye's locations of tropical cyclones within the 800 km circle were selected. To assess tropical cyclone impact, we used and modified the Tropical Cyclone Potential Index (TCI) which was introduced by [26]. Then monthly TCI was computed as Equation 3 and 4:

$$TCI = \sum_{i=1}^n w_i v_i^2 \quad (3)$$

$$w_i = 1 - \frac{d_i}{800} \quad (4)$$

where  $n$  is the number of points of 6-hour tropical cyclones in the circle;  $v_i$  is the maximum wind speed near the tropical cyclone center  $i$ ;  $w_i$  is the weight of the tropical cyclone center  $i$  which was calculated by its inverse distance to the study area; and  $d_i$  is the distance between the tropical cyclone center and the study area centroid (km).

### 2.2.2 Saline intrusion

Saline intrusion is the most influential factor that impacts agricultural production in My Xuyen district. Saltwater intrudes into My Xuyen district through the My Thanh River which are directly connected to the East Sea [27]. Salinity data from 2016 to 2019 at Nga Ba Vam Leo (located in Hoa Tu 2, Fig. 1) was collected by the Irrigation Management Station of My Xuyen district. These data of salinity were analyzed the monthly frequency of salt stress. The levels of salt stress are identified based on the cultivated crops and their stages. Generally, salinity levels of higher than 2 dS/m can reduce rice yield regarding the timing of salt stress and rice variety [28]. According to [29], the agricultural crops are not affected by the electrical conductivity (EC) of irrigation water which is lower than 0.7 dS/m. When the EC is higher than 0.7 dS/m, the agricultural crops begin to be damaged slightly. The crops are severely affected by the EC of higher than 3.0 dS/m. This is a common classification for salt stress of irrigation water for agriculture and this highly agrees with the salinity hazard of irrigation water defined by [17,30]. Specifically, each agricultural crop has a different capacity to adapt to saline water. For instance, the effects of saline water on rice yield were evaluated by [29] and are presented in Table 1. Total dissolved solids (TDS) are the common data of water salinity and they were estimated by using its relationship with EC. The average ratio of total dissolved solids and EC is 0.64 [31].

**Table 1.** Salinity hazard categories of irrigation water for rice crops [29].

EC (dS/m)	TDS (g/l)	Category	Effects on rice crops
$EC < 2.0$	$TDS < 1.3$	None	Rare effect on rice yield
$2.0 \leq EC < 3.4$	$1.3 \leq TDS < 2.2$	Slight	Reduction of 25% rice yield
$3.4 \leq EC \leq 4.8$	$2.2 \leq TDS \leq 3.1$	Moderate	Reduction of 50% rice yield
$EC > 4.8$	$TDS > 3.1$	Severe	Reduction of over 50% rice yield or destruction of rice crops

The salinity data collected were used to analyze the monthly frequency of the selected salinity levels. To assess the effects of saline water on rice crops, we defined the Salinity Potential Index (SPI) based on salinity levels and their frequency, presented as Equation 5.

$$SPI = \sum_{i=1}^3 n_i w_i \quad (5)$$

where  $i$  is the number of salinity hazard categories,  $n_i$  is the number of salinity occurrences of the category  $i$ ,  $w_i$  is the category weights which are equal to 0.25, 0.5, and 1 for *slight*, *moderate*, and *severe* categories respectively.

## 2.3 Susceptibility of rice crops in the rice-based cropping system

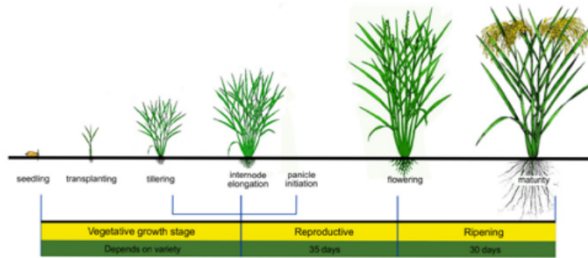
Rice is the major agricultural crop in My Xuyen district and the rice-based farming systems are double rice crops and shrimp-rice crops. Rice crops are highly susceptible to the effects of tropical cyclones and salinity in irrigation water. Each type of these hazardous events has a different way to influence rice crops.

### 2.3.1 Effects of tropical cyclones

The tropical cyclones damage the rice crops due to high wind velocities which lead to injury of plant organs. [12] found that the highest rice vulnerability to tropical cyclones is the heading stage and assumed that the fragility curve of rice plants can be formulated by the Weibull distribution. Therefore, rice vulnerability to tropical cyclones was computed from the damage ratios introduced by [12].

### 2.3.2 Effects of saline intrusion

The rice crops are highly vulnerable to salt stress and the damages correspond to their growth stages. The rice crops are really sensitive to salinity, particularly at the seedling stage [16,32]. By another way, saline irrigation water increases salt accumulation in the crop root zone and this causes the rice crops to not be able to provide sufficient water. Moreover, saline irrigation water can slow the growth rate of rice plants, leading to a reduction or a loss of rice yield. Salinity in irrigation water differently influences rice growth and yield during the growing stages. Thus we used the cropping calendar of the farming systems in order to analyze the susceptibility of the rice crops. During the seedling stage, the effects of saline water on rice growth at different timing during the vegetative stage are relatively similar. These effects in the reproductive phase are slightly higher in the vegetative phase [21]. In this study, the susceptibility of rice was indicated by the reduction of rice yields. The reduction of rice yields at different timing of salinity was computed based on experimental data of [33]. These reductions are considerably changed under different salinity levels, illustrated in Table 2. Rice growth has similar patterns of responses to the different salinity levels during growing phases (Fig. 2). The panicle initiation is the most susceptible stage in which rice yield can be reduced by a half due to the effects of 4 dS/m salinity. We used average reduction of rice yield due to 2 and 4 dS/m salinity for indicating rice sensitivity during growth phases. At the seedling stage, rice survival is about 70.2% because of impacts of 3.3 dS/m salinity [34]. Response of the rice crops to salinity is highly varied because of rice varieties. We assumed that the rice varieties cultivated in My Xuyen district have a similar capacity to respond to salinity and tropical cyclones to those in experiments of [12,33].



**Fig. 2.** The growth stages of rice [18].

**Table 2.** Reduction of rice yield at different timing of salinity [33].

EC (dS/m)	Tillering	Panicle initiation	Heading	Ripening
2	26%	43%	9%	4%
4	33%	50%	13%	3%
Average	30%	46%	11%	4%

The decreased percentages of rice yields were normalized. Values of the vulnerability index were normalized on a scale from 0 to 1 where vulnerability is lowest or highest respectively. These vulnerabilities are grouped into five categories, presented in Table 3.

**Table 3.** Categories of vulnerability.

Category	Hazard and vulnerability	Risk
Very low	0 – 0.2	0 – 0.04
Low	0.2 – 0.4	0.04 – 0.16
Moderate	0.4 – 0.6	0.16 – 0.36
High	0.6 – 0.8	0.36 – 0.64
Very high	0.8 - 1	0.64 – 1

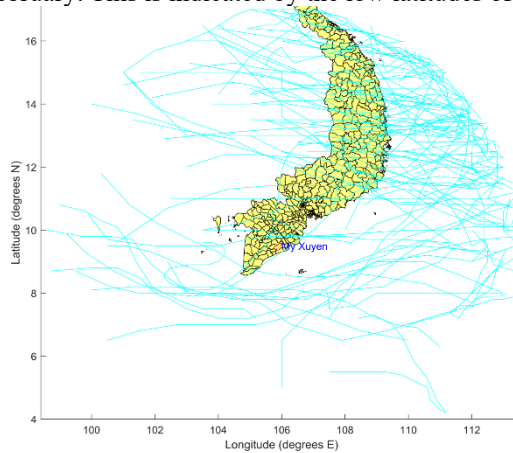
### 3 Results and discussion

Many regions are exposed to a number of natural hazards depending on their spatial characteristics. There are several specialized hazards in coastal areas such as tropical cyclones and saline intrusion. It is evident that these natural hazards cause huge damage to agricultural production in the coastal areas. Therefore, the outputs of the hazard and vulnerability assessment assist to deal with the risks of these phenomena. In this section, we present the results of the hazard, vulnerability, and risk assessment of the mentioned hazardous events, influencing the rice crops in My Xuyen district.

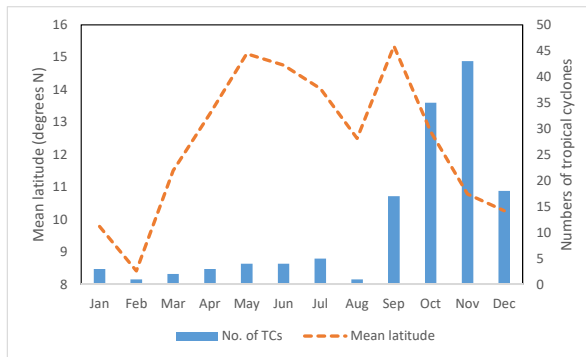
#### 3.1 Temporal hazard assessment

Fig. 3 shows the tropical cyclone tracks within the region of potential effects from 1951 to 2019. There are 136 tropical cyclones that occurred in the region. The tropical cyclones originate from the eastern-oriented directions, developing in the Pacific Ocean. Generally, tropical cyclones occur during the southwest monsoon season. The monthly numbers of tropical cyclones are presented Fig. 4. My Xuyen has high potential effects of tropical cyclones from September to December, particularly in October and November which contribute to over a half of the total tropical cyclone number. The tropical cyclones are rarely approached the southern coast (My Xuyen district) while they hit the central and northern

parts of Vietnam [35]. It is obviously evident that the tropical cyclones move to the south from November to February. This is indicated by the low latitudes of tropical cyclones.



**Fig. 3.** Tropical cyclone tracks (1951-2019) within the region in which they can affect My Xuyen.



**Fig. 4.** Monthly numbers and mean latitude of tropical cyclones from 1951 to 2019.

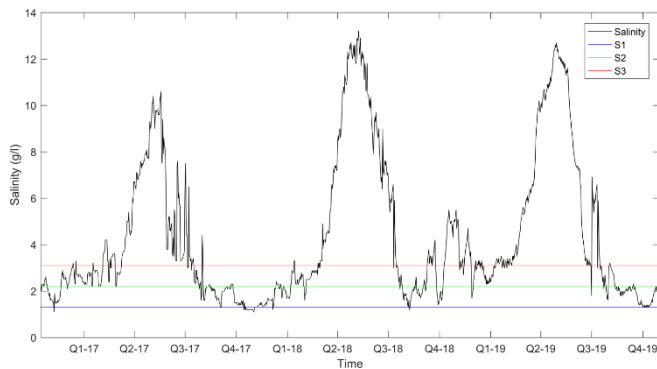
We calculated the monthly TCI of all tropical cyclones from 1951 to 2019 (Table 4) in order to identify stress timing due to tropical cyclones. The results clearly show that November has the highest TCI value, followed by October since these two months have the greatest occurrence of tropical cyclones. Although September and December have similar numbers of tropical cyclones, the TCI value of December is considerably higher than that of September. This happens because tropical cyclones in December tend to get closer to My Xuyen. Consequently, October and November are the most hazardous periods, which are categorized as *high* and *very high* respectively.

**Table 4.** Hazard indexes of tropical cyclones and salinity.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average TCI	49	482	131	173	336	242	160	11	1285	8646	13065	4709
$HI_{Tropical}$ cyclones	0.00	0.04	0.01	0.01	0.03	0.02	0.01	0.00	0.10	0.66	1.00	0.36
$HI_{Salinity}$	0.60	0.76	0.96	1.00	1.00	0.98	0.68	0.34	0.43	0.40	0.46	0.48
$HI$	0.59	0.77	0.95	1.00	1.00	0.98	0.68	0.34	0.44	0.52	0.63	0.54
	Very low		Low		Moderate		High				Very high	

Saltwater intrudes into My Xuyen district through the My Thanh River (Fig. 1). The My Thanh River is strongly dominated by the coastal processes and marginally controlled by the fluvial process. Thus surface water resources become saline due to the effects of the coastal processes. Fig. 5 presents variations of daily maximum salinity at Nga Ba Vam Leo station from 2016 to 2019. It obviously depicts that saltwater intrusion varies seasonally. Specifically, salinity reaches the highest level in April or May when river flows are low in the dry season; in contrast, salinity becomes lowest in September coinciding with high river flows in the rainy season in the Mekong Delta. However, salinity at Nga Ba Vam Leo is generally higher than the S1 level in which rice yield can be reduced by 25%. Therefore, surface water resources at Nga Ba Vam Leo need to be used for rice irrigation. This results in high values of salinity hazard index over the year. The salinity hazard indexes are usually categorized as *moderate*, *high*, and *very high* (Table 4).

Based on the rates of saline intrusion and tropical cyclones influencing agricultural cropping systems in My Xuyen, the saline intrusion is the main phenomenon damaging rice crops while tropical cyclones have much less impact. The ratio of saline intrusion to tropical cyclones impacts is approximately 85:15. This ratio is relatively reasonable because the probability of tropical cyclones is low while saline intrusion frequently happens in My Xuyen. The multiple hazard index (illustrated in Table 4) indicates that May-June is the most hazardous period for rice production. This calculation agrees with the cropping calendar of the double rice cropping system in My Xuyen. This period is free in the cropping calendar [36] due to the *very high* hazard index. The lowest hazard appears in August, followed by a *moderate* hazard period. Thus rice is cultivated during this period even in the rice-shrimp cropping system.



**Fig. 5.** Daily maximum salinity at Nga Ba Vam Leo. S1, S2, and S3 are critical levels that reduce rice yields of 25%, 50%, and 75% respectively.

### 3.2 Vulnerability

Table 5 shows temporal variations of the vulnerability index of a rice crop which indicates potential effects of tropical cyclones and salinity, damaging at different growth phases. We found that rice crops respond to tropical cyclones and salinity differently. Rice is most vulnerable to tropical cyclones at the heading stage and to salinity at the panicle initiation phase. Noticeably, the first half of the rice crop is highly vulnerable to salinity while the second half is considerably damaged due to tropical cyclones. The combined vulnerability index is averaged and normalized. It shows that the panicle initiation stage has the highest value of the combined vulnerability index, followed by the heading stage with an index of 0.66.



**Table 5.** Vulnerability index of a rice crop.

Growth phase	Seedling	Tillering	Panicle initiation	Heading	Ripening	Harvesting
Days after sowing	1	20	50	70	100	105
Vulnerability to tropical cyclones	0.00	0.33	0.87	1.00	0.77	0.67
Vulnerability to salinity	0.64	0.64	1.00	0.23	0.08	0.08
Combined vulnerability index	0.34	0.52	1.00	0.66	0.45	0.4

Rice cultivated in My Xuyen are usually short-duration varieties that mature in a range of 105-120 days. This coincided with surveyed data in My Xuyen district recently [36]. Table 6 presents the cropping calendar of the double rice and rice-shrimp cropping system in My Xuyen. The double rice cropping system includes Summer-Autumn (from June to September) and Winter-Spring (October to January) crops. The rice crop in the rice-shrimp cropping system is cultivated from September to December. The cropping calendar of each system was used for computing the vulnerability index which is depicted in Table 6. My Xuyen district has highly potential damage to rice in October and November because it has the largest area of rice production at the reproductive phase in both cropping systems. In contrast, there is no damage to rice crops from February to May because of no rice grown during this period. This period obviously coincided with the highest salinity in My Xuyen. It can be explained that the local community and farmers may have a measure to adapt to saline intrusion by adjusting the cropping calendar. Consequently, the saline intrusion is the most hazardous event in this area.

**Table 6.** Cropping calendar of rice-based farming systems in My Xuyen [36] and rice vulnerability index.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Double rice						Summer-Autumn			Winter-Spring			
Rice-Shrimp			Shrimp					Winter-Spring				
Vulnerability index	0.17	0.00	0.00	0.00	0.00	0.25	0.55	0.44	0.43	0.81	1.00	0.64
	Very low	Low	Moderate			High		Very high				

### 3.3 Multi-hazard risk

Based on the hazard and vulnerability identification, monthly risk indexes indicating the possibility of rice damage or loss due to effects of tropical cyclones and saline intrusion, are presented in Table 7. October and November belong to the *high* category while February-May have no risk. The rice crop is at no risk from February to May and this has resulted from no rice crop cultivated during this period. The *high* risk of rice production in October and November occurs because of *very high* vulnerability and *high* hazard. Results of the temporal analysis have a reasonable agreement with [37] outputs of risk analysis for the coastal VMD in general.

**Table 7.** Monthly risk of rice to multiple hazards.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Risk	0.10	0.00	0.00	0.00	0.00	0.24	0.37	0.15	0.19	0.42	0.63	0.34
	Very low		Low		Moderate		High			Very high		

The nature of risks is considerably useful for assessing the potential impacts of tropical cyclones and saltwater intrusion on rice production. It is noticed that the damages of agricultural crops vary with the timing of the hazards and crop growth stages. Therefore, to reduce the risks, it needs to reduce hazards or/and vulnerability. First, the hazards can be reduced by improving the early warning system. The hazardous phenomena are tropical cyclones and salinity which are possibly predicted by their dominated factors. For example, tropical cyclones are predicted by several predominant factors [38,39]. The salinity is usually projected by the El Niño–Southern Oscillation indexes [40] or water discharge of the Mekong River [41]. In addition, a structure such as sluice gates is a common measure to prevent saline intrusion in coastal areas. Second, there are some solutions to reduce the vulnerability of rice-based cropping systems, including using salt-tolerant varieties, adjusting the cropping calendar, and changing to other agricultural crops [24,42]. The results of risk assessment can help the local community become more resilient in rice cultivation to natural hazardous events.

## 4 Conclusions

We assessed multiple natural hazards of tropical cyclones and saline intrusion. These hazardous events are the major factors, causing significant damages to rice crops in My Xuyen district. To assess the risk of the multiple natural hazards, we used a framework of risk on rice crops in a coastal area (My Xuyen, Soc Trang). The study primarily focused on the evaluation of the potential impacts of the mentioned hazards on rice crops. A temporal analysis was embedded in risk assessment because rice crops vary seasonally.

The study has shown that rice crops may face extreme salinity from March to June while it deals with tropical cyclones in October and November. These hazards have various effects on rice crops. Rice crops are considerably susceptible to salinity during the first half of the growing period and to tropical cyclones during the other half. In general, therefore, the results show that rice crops are sharply susceptible in the reproduction phase to the combination of salinity and tropical cyclones. For rice cultivation in My Xuyen, it is considerably vulnerable to these hazards in October and November based on the cropping calendar. We found that the rice crops are at *high* risk in October and November. Our findings are that saline intrusion reaches the highest level in April and May, but the rice crop was at no risk because of no rice crop cultivated during this period.

The multiple hazard assessment provides essential information for the case study in order to create awareness for natural disaster mitigation. In addition, the integrated result of multiple hazards is much more simple than those of each hazard in providing information to planners and decision-makers because many numbers and scales can be confusing and cumbersome to them. If the results of multi-hazards and risk assessment are used efficiently, it can reduce damage or loss of rice crops/yield. However, this needs an effort of users who convey the information to the natural disaster mitigation procedure. An implication of these findings is to assist decision-makers, planners, and managers in mitigation and adaptation strategies.

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